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EXPERIMENTAL EFFECT OF GAS FLOW TRANSIENTS ON THE HEAT RELEASE OF BURNING LIQUID DROPS IN A ROCKET COMBUSTOR

By Marcus F. Heidmann

Lewis Research Center
Cleveland, Ohio

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SUMMARY

The change in heat release caused by drop shattering was qualitatively evaluated in a small-scale rocket combustor. A single 0.089-inch-diameter liquid-heptane jet was reacted with uniformly distributed gaseous oxygen in a 2-inch-diameter cylindrical combustor. Gas flow transients were imposed on the burning drops produced by the jet when orifice-type area restrictors were inserted in the gas flow path. The arrangement of components was coaxial. Restrictor size and position were varied for various combustor pressure levels. Combustor performance with and without restrictors was compared to evaluate the effect of the flow transients.

The experimental study consisted of two parts: (1) exploratory tests to determine the region of sensitivity of the burning drops to flow transients and (2) systematic variations to obtain correlating gas flow parameters.

The exploratory tests showed that, with near sonic flow at the restrictor, the transient caused approximately 55 percent of the heptane entering the restrictor region to vaporize and burn. The change in heat release was at a maximum immediately following the restrictor and was complete in less than 6 inches. Drop breakup or shattering was the apparent cause of the increase in heat release.

The systematic variation of restrictor size and pressure level showed no critical condition that divided transients with and without an increase in heat release. Rather, heat release increased uniformly with an increase in the severity of the transient. A correlation of the experimental data on the basis of aerodynamic forces alone could not be obtained. Results showed an empirical correlation with gas momentum at the minimum area of the restrictor.

INTRODUCTION

The breakup or shattering of burning liquid drops is frequently postulated as a cause for abrupt changes in the heat-release rate in rocket engine combustors (ref. 1), and analytical attempts to predict drop stability in a gas stream have received considerable attention. The analyses have ranged from the static stability criteria of Weber to a variety of time-varying pressure and velocity conditions (refs. 2 to 4). Experimental confirmation has been obtained in many instances (refs. 4 to 7). Theoretical predictions and experimental verification have, however, become increasingly complex for many flow conditions that vary uniquely with time. In addition to drop stability criteria, the size of drops produced by breakup is generally not known. This inability to prescribe drop stability and resultant drop size for most transient conditions precludes any prediction of changes in heat release caused by transients in rocket combustors.

The present study was made to obtain at least qualitative data on the change in heat release that may be expected from aerodynamic transients.

The experimental technique used herein was to measure the change in performance caused by an area restrictor inserted within a cylindrical combustor in a region of incomplete combustion. Under these conditions burning liquid drops pass through the velocity and density gradients caused by the restrictor. The time period of the transient is dependent on the velocity of the drops through the gradients. Varying the size of the restrictor allows large variations in velocity and density to be obtained and the sensitivity of burning drops to such disturbances to be determined. Variations in the length of the combustor following the restrictor provided an estimate of the time history of heat release that followed the gas flow transient.

An analysis of the performance data gave the fraction of liquid induced to burn by the transient and also the gas flow properties at the restrictor throat. Correlation parameters were based on these values.

COMBUSTOR DESIGN

The combustor and restrictor configurations are shown in figure 1. The injector, cylindrical chambers, and nozzles were separable units. Heptane was injected as a single axial jet, and gaseous oxygen was introduced to give nearly uniform velocity across the combustor at the point of fuel injection. Under nonburning conditions the dispersion of the heptane jet was low, and it did not impinge on the exhaust nozzle or area restrictor. An assortment of cylindrical sections was used to vary chamber length and to position an area restrictor between the injector and the exhaust nozzle. Gaseous oxygen and liquid heptane were used as propellants. An oxygen-fuel weight ratio of 2.4, a heptane-injection velocity of 140 feet per second, and a total flow rate of 0.9 pound per second were the standard operating conditions. The theoretical characteristic velocity c^* at this condition was 5940 feet per second. Reported performance values are averages obtained from at least four test firings and are based on pressure measurements made near the exhaust nozzle. Pressure measurements upstream of the restrictor were used to determine the pressure recovery factor, which was nearly constant at 0.96.

TEST PROCEDURE

Reference Performance

The combustor c* performance without an area restrictor was evaluated for chamber lengths of 8 and 16 inches and for exhaust-nozzle diameters of 0.5935, 0.790, and 0.935 inch. This performance evaluation provided reference conditions for subsequent tests with area restrictors.

Exploratory Tests

Initial tests used the area restrictor shown in figure 1(a) to explore the region of sensitivity of the jet to flow disturbances. The area-change contours of the restrictor and exhaust nozzle were similar for these tests. An 8-inch length of combustor was used between the injector and the area restrictor. Performance evaluations were made for a range of chamber lengths between the restrictor and exhaust nozzle. The following combinations of restrictors and exhaust nozzles were used:

Restrictor diameter, in.	Exhaust-nozzle diameter, in.
1.37	0.935
1.37	.790
.993	.790
.790	.790
.790	.5935

Systematic Tests

After the exploratory tests a restrictor design was needed for a systematic study of flow perturbations. The area restrictors used in the exploratory tests had a relatively constant half-angle approach of 45° and a sudden enlargement following the throat. Streamline flow both upstream and downstream of the throat could not be assumed, and, therefore, the velocity and pressure variation through an area change could not be computed. Restrictor designs giving streamline flow, however, necessitated very long area-change sections. These sections were undesirable for the following reasons: First, the effect of gas dynamic transients of the order of 1 millisecond were of primary interest. The passage of drops through long sections would simulate transients much longer in duration. Second, a history of events following a flow transient was of interest. These events would occur within long area-change sections and could not be traced by evaluating c* performance as a function of chamber length. Since streamline flow could not be obtained, an abrupt change produced by a rounded orifice in a thin plate was used for simplicity.

The area-restrictor design used in the systematic study is shown in figure

1(b). The combinations of restrictor and exhaust nozzle used are shown in the following table:

Restrictor diameter, in.	Exhaust-nozzle diameter, in.		
1.256	0.5935	0.789	0.993
1.166	------		
1.076	.5935		
.997	------		
.918	.5935		
.786	------		
.675	------		
.566	------		

These combinations were used with an 8-inch chamber length preceding the restrictor and a 6-inch chamber length following the restrictor. Exploratory tests indicated that the effect of an area restrictor on heat release was relatively complete within the 6-inch length.

Restrictor Position and Contour

A series of evaluations was made with a 0.786-inch-diameter restrictor and a 0.789-inch-diameter exhaust nozzle in which the length of the upstream chamber section was varied. Upstream chamber-length variations were made to test the sensitivity of the liquid jet to transients at various distances from the point of origin of the liquid jet. Downstream chamber-length variations were also made. The nozzle and restrictor combination was comparable in size to the combination used in one of the exploratory tests. Restrictor contour was the primary difference in these tests; its effect can be inferred by a comparison of results.

RESULTS AND DISCUSSION

The c^* performance and computed combustion parameters for all combustor configurations are presented in table I.

Reference Performance

The performance of the combustor without a restrictor was relatively low, c^* being of the order of 50 percent of the theoretical value. The low performance was desirable because it assured the presence of burning liquid within the entire combustor. An analysis of the performance on the basis of a vaporization-limited combustion model, as in reference 8, indicates that the amount of heptane burned $\mathscr{F}$ is only 10 to 15 percent at a distance of 8 inches from the injector.

The reference performance shown in figure 2 was used to determine the comparative effect of a restrictor on performance. The performance is a function of the combustor length and the pressure that varied with nozzle area and with completeness of combustion. Reference 9 contains a more thorough test of performance as a function of nozzle area and combustor length. The results of these tests and the analytical studies of drop vaporization reported in reference 8 were used as a basis for the extrapolation and interpolations in figure 2.

The combustion parameters shown in table I were computed by using the fraction of heptane burned at the entrance of the area restrictor obtained from figure 2. The mixture ratio of the burned gases at the restrictor entrance was computed with knowledge of the fraction of heptane burned. The theoretical thermodynamic gas properties for the propellant combination at these computed mixture ratios and the continuity equation were then used to calculate velocity, density, and Mach number at the restrictor entrance. The value of these parameters at the restrictor throat was computed by the assumption of adiabatic-isentropic flow at constant total temperature with no mass addition and negligible liquid volume. The relative gas velocity is the difference between the gas velocity at the restrictor throat and an assumed drop velocity of 140 feet per second, which is equal to the injection velocity. The injection velocity was used because the computed deceleration of the injected liquid is negligible for these test conditions.

Exploratory Tests

Performance change. - Figure 3 shows the performance obtained with the various combinations of area restrictor and exhaust nozzle in the exploratory tests. Performance is shown as a function of total combustor length and two performance values c^* and $\mathscr{F}$ are also shown. The performance obtained without an area restrictor is found on each performance curve. This presentation gives a qualitative comparison of the effect of the area restrictor on performance. These performance comparisons are only qualitative in that combustor pressure may vary significantly between conditions with and without an area restrictor. A more exact comparison based on constant pressure is presented in the subsequent analysis of the data.

These exploratory tests show that a significant performance change can occur with an area restrictor. In some instances c^* efficiency is raised from 50 to about 85 percent. The vaporized and burned fuel increased from about 25 to 60 percent. The largest performance changes occurred with small restrictors. With a given size restrictor, however, a change in exhaust-nozzle size did not appreciably affect performance (compare fig. 3(a) with 3(b) and 3(d) with 3(e)). These tests were not conclusive, but they did indicate that performance increased with an increase in velocity or density at the restrictor throat as shown by table I. The relation to these parameters could not be established from these data.

Combustion delay. - Figure 3 also shows that the performance increase depends on the chamber length following the area restrictor. A large rate of increase immediately follows the restrictor, and at the 6-inch length this rate is comparable with the increase in a combustor without an area restrictor. If fuel drops proceed through the transient at constant velocity, the rate of performance increase with length is indicative of the combustion rate. In some instances the slope of the performance curve with and without a restrictor indicates a combustor rate change of about one order of magnitude. The assumption of constant drop velocity also permits an estimation of the time required to change the combustion rate substantially. The largest and most abrupt performance change occurred with the 0.790-inch restrictor and exhaust-nozzle diameter. The abrupt change centered in the region 1 inch downstream of the restrictor. With the assumption of a drop velocity the same as the injection velocity of 140 feet per second, the change occurred about 0.6 millisecond after the disturbance. Although precision cannot be claimed for this technique of evaluating time delays, the observed value is comparable to that reported in reference 4. Reference 4 states that breaking times were equal to or less than one-half the period of natural oscillation of liquid drops. If 0.089-inch-diameter heptane drops are assumed, this interval is equal to about 7 to 10 milliseconds. Qualitatively, the results obtained appear to agree with the cold flow studies.

Performance analysis. - A more complete analysis of the data was made for an evaluation of the effect of an area restrictor under conditions of constant combustor pressure. A comparison factor was derived for this purpose. This factor is the ratio of the performance increase obtained with a restrictor to the maximum available increase that could have been obtained. All values are with reference to the pressure level while a restrictor is used.

The performance increase factor is expressed as follows:

$$\frac{\text{increase in heptane burned}}{\text{available increase}} = \left(\frac{\mathscr{F}_{exp} - \mathscr{F}_x}{1 - \mathscr{F}_x}\right)_p$$

where $\mathscr{F}_{exp}$ is the percent of heptane vaporized and burned while an area restrictor is used, $\mathscr{F}_x$ is the percent at the exhaust nozzle in an equal length combustor without a restrictor, and the subscript p denotes an evaluation at constant combustor pressure. These values may be obtained from figure 2.

The performance increase factor is shown in figure 4 as a function of length of combustor following the restrictor for the exploratory test conditions. The largest value obtained was 0.45. This indicates that 45 percent of the heptane that normally would not burn was induced to burn by the action of the flow transient.

The heat-release conditions following the restrictor were analyzed on the basis of a vaporization model (ref. 10) to evaluate qualitatively the drop size needed to produce such performance changes with length. For performance of the type shown in figures 3(d) and 3(e), a mean drop diameter of less than 50 microns is required. Without a restrictor the performance indicates a drop diameter of the order of 2000 microns. The analysis implies that drop breakup or shattering has occurred.

Systematic Tests

The c^* performance and the performance increase factor obtained from the systematic study of restrictor and exhaust-nozzle-area combinations are shown in figure 5. The data are for a 6-inch length of combustor following the restrictor, and it is assumed that the entire performance increase that was due to the flow disturbance had been attained in this length. Figure 5 shows that the performance increases uniformly with a decrease in restrictor area over the range of restrictor sizes used in this study. The threshold value for a performance increase appears to be near a restrictor diameter of 1.4 inches, which is about one-half the combustor area. The gas flow was almost sonic with the smallest restrictor, and about 55 percent of the available increase was obtained. One point of interest in figure 5 is that the performance increase factor is insensitive to the diameter of the exhaust nozzles.

A correlation of this data was attempted on the basis of previous analytical models for drop shattering. Most analytical models are based on a distortion due to aerodynamic pressure on the drop. This pressure is proportional to the product of gas density and the square of relative gas velocity. Figure 6 shows the performance increase factor as a function of this force at the restrictor throat. The performance increase does not appear to be singularly dependent on this force. Additional factors such as drop acceleration, a distribution of drop sizes, and variable drag coefficients were included in the aerodynamic force parameter with no significant improvement in the correlation.

A correlation of performance increase with Weber number is similar to the curves shown in figure 6 because aerodynamic pressure is the primary variable. With the assumption of a drop diameter of 0.089 inch, these tests represent Weber number conditions exceeding 10,000.

Empirical correlations of the performance data were attempted. Figure 7 shows such a correlation relating the performance increase factor to the gas flow momentum. The gas flow momentum in this case is the product of the restrictor throat velocity and density. Available data approach a single-value function; previous analytical studies provide no direct basis for such a correlation. The performance increase factor is shown in figure 8 as a function of the product of gas density and relative drop velocity at the restrictor throat. The deviation from a single-value function is somewhat larger than for the correlation with gas flow momentum; however, this deviation may not be significant when the precision in the evaluation of these parameters is considered. The product of density and relative gas velocity is a measure of the momentum imparted to the drop. This momentum is also related to the Reynolds number for the drops. Neither of these factors would directly provide a criterion for drop stability. Stability may be indirectly related to Reynolds number in that it is an index of boundary-layer conditions surrounding the drop or the distribution of pressure forces on the drop surface.

Impingement of the liquid drop on the restrictor surface cannot be ignored. If jet dispersion is extensive, the number of drops striking the restrictor surface would vary inversely with restrictor diameter. A high combustion rate of these drops would give a performance increase that is dependent on restrictor size. Combustion photographs were taken by using transparent plastic cylindrical combustor sections to investigate this possibility. The photographs showed that dispersion was small, and impingement of drops on the surface appeared negligible even for the smallest restrictor size. The amount of liquid striking the surface could not in itself account for the performance change.

Restrictor Position and Contour

The performance increase in an 8-inch length of combustor following a restrictor placed at various distances from the jet origin is shown in figure 9. The performance increase becomes uniformly larger with distance from the jet origin. No change in performance increase would be expected if the strength of the flow transient and the sensitivity of the jet to a transient remained constant. A change in the flow transient was present. The dashed curve in figure 9 is the predicted value of performance increase if the correlation with gas flow momentum is assumed to be correct. This momentum effect is relatively small and indicates that jet sensitivity increases with jet length. The uniform change in performance suggests that abrupt transitions do not occur in the disintegration process of the jet.

The performance increase obtained with a thin-plate and a nozzle-type restrictor is shown in figure 10. A larger and more rapid increase was obtained with the nozzle-type restrictor. A probable explanation for this difference is that flow conditions at and near the throat were maintained for a longer period of time with the nozzle-type restrictor. The cumulative effect, therefore, would be larger with a nozzle-type than with a thin-plate restrictor.

CONCLUDING REMARKS

The velocity and pressure gradients in the vicinity of the restrictor may contribute to drop instability. A drop within a pressure gradient will have unequal pressure forces on its upstream and downstream surfaces that will distort the drop and may cause breakup. Pressure gradients of the order of 100 pounds per square inch per inch of combustor length were established for many of the test conditions in this study. This gradient would produce a pressure difference of 8 pounds per square inch on a 2000-micron drop. This force is added to the aerodynamic force, which is comparable in magnitude (fig. 6). Pressure gradients are established in all flow transients and should be included in the complex analytical model for drop stability.

Shock-tube studies of drop shattering in references 4, 11, and 12 show liquid being sheared off the surface of a drop as a fine mist of small drops by the shock action that leaves a distorted mass of the original drop. The proportion of mist and distorted mass varies with shock strength. Results of this study agree with such a model. A uniform change in heat release with restrictor size was obtained. This heat-release pattern could be a measure of the mist sheared off the drops as the strength of the flow transient was varied. With such a model, a narrow-band critical region does not exist.

An oscillatory change in heat release is frequently postulated as a means for driving combustion instability. Drop breakup may, in some instances, provide the energy required to sustain an oscillation. If combustion instability depends on the phenomenon observed in this study, an oscillatory condition of less than 1000 cycles per second would be most susceptible to drop breakup. The observed time delays are such that higher frequencies would cause inefficient coupling.

Another prerequisite for instability may be a high level of heat release (ref. 10). The phenomenon observed in this study could produce a continuous high-level heat-release condition. If small drops are sheared from the surface of large drops during each oscillation, a quasi-steady-state condition exists. The mist of drops produced by each oscillation overlaps in its heat-release pattern to cause a higher level of combustion rate. Flow transients could, therefore, cause a substantial increase in the level of heat release and in this manner could be a prerequisite for sustained oscillations.

The technique employed to impose a transient on burning drops could be expanded to obtain more quantitative data on drop stability. Optical drop tracking would be necessary to establish an accurate time base for the phenomenon and to evaluate drop characteristics. Measurements in the region of the restrictor are also necessary in order to define the velocity and pressure gradients. With knowledge of these parameters, the time history of the phenomenon could be established and stability criteria more thoroughly investigated.

SUMMARY OF RESULTS

Flow transients were experienced by burning liquid drops passing through the pressure and velocity gradients caused by an area restrictor in a rocket combustor. A comparison of the performance with and without a restrictor gave the following results:

1. The performance change increased uniformly with a decrease in restrictor size. A restrictor area of about one-half the combustor area gave the first measurable performance change. Maximum changes were obtained with critical flow in the restrictor.

2. An analysis of the performance change showed that up to 45 percent of the heptane normally not burned was induced to burn because of the flow transient.

3. Drop breakup or shattering is implied by an analysis of the heat-release pattern following the flow transient.

4. The percent of heptane burned because of the action of the flow transient showed a correlation with the gas flow momentum at the minimum area of the restrictor.

Lewis Research Center
National Aeronautics and Space Administration
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TABLE I. - COMBUSTOR PERFORMANCE

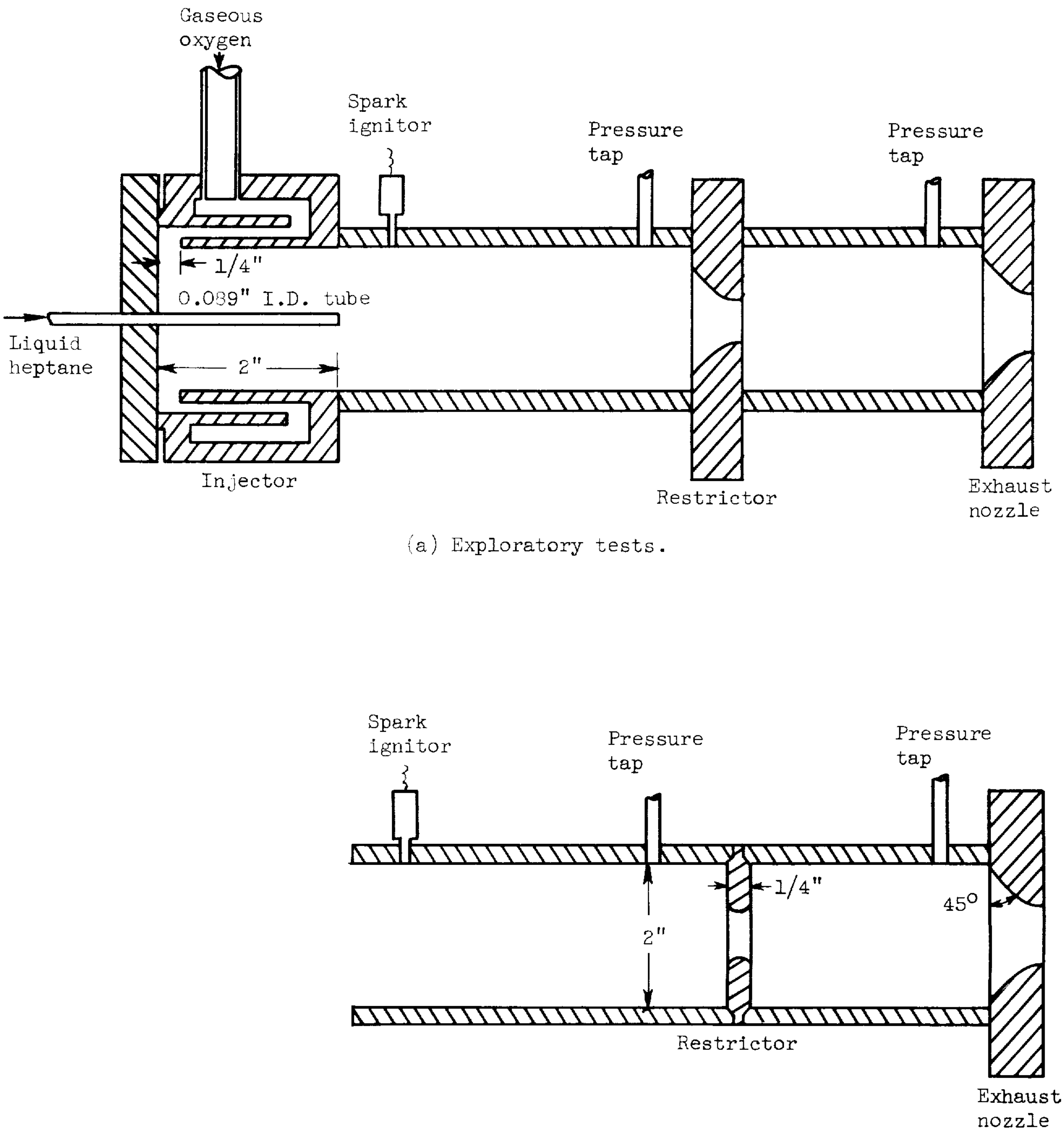
Exhaust-nozzle diameter, in.	Restrictor diameter, in.	Combustor length, in.		Characteristic velocity, c*, ft/sec	Combustor pressure, lb/sq in. abs	Heptane burned, percent			Performance at entrance to restrictor			Performance at restrictor throat						Performance increase factor[c]
		Before restrictor	After restrictor			At restrictor throat	Total, With restrictor	Total, Without restrictor	Velocity, ft/sec	Density, lb/cu ft	Mach number	Velocity, ft/sec	Density, lb/cu ft	Mach number	Relative gas velocity, ft/sec	Aerodynamic force[a], lb/sq in.	Gas momentum[b], lb/(sq ft)(sec)	
Exploratory tests																		
0.233	1.3	6	1.50	3000	122	12.0	18.2	16.3	253	0.107	0.111	540	0.103	0.254	---	---	---	0.0227
.233	1.3		4.50	3370	137	10.3	24.5	13.3	231	.132	.094	510	.125	.212	---	---	---	.064
.233	1.3		6.5	3570	146	10.5	28.3	21.7	212	.143	.085	469	.140	.187	---	---	---	.087
[illegible]	.730		.75	3270	156	11.7	22.2	12.7	175	.172	.076	1322	.148	.540	---	---	---	.108
			2.5	4030	254	16.8	52.7	18.6	155	.200	.067	1090	.183	.401	---	---	---	.411
			4.5	4780	271	17.1	56.0	22.4	134	.202	.066	1090	.188	.395	---	---	---	.432
			6.5	4930	261	17.7	60.3	24.5	122	.206	.061	1060	.191	.385	---	---	---	.473
	.933		2.5	3890	210	13.2	31.0	18.1	170	.151	.067	720	.173	.284	---	---	---	.174
	.933		4.5	4270	243	14.3	43.3	20.7	160	.183	.061	670	.188	.264	---	---	---	.295
	.933		6.5	4480	254	11.3	49.0	22.4	157	.187	.059	662	.191	.248	---	---	---	.342
	1.37		1.5	2890	165	10.7	16.3	12.6	191	.150	.081	408	.154	.174	---	---	---	.040
	1.37		4.5	3230	184	11.1	22.0	17.4	177	.178	.072	383	.165	.155	---	---	---	.055
	1.37		6.5	3460	187	12.3	27.0	19.7	173	.177	.062	371	.17	.123	---	---	---	.079
.533	.730		.75	3960	336[d]	11.2	36.4	23.2	120	.220	.041	508	.211	.276	---	---	---	.177
.533	.730		4.5	4810	408[d]	[illegible]	57.3	33.7	112	.240	.038	742	.232	.242	---	---	---	.350
.533	.730		6.5	4870	442[d]	[illegible]	61.4	38.1	110	.241	.035	731	.237	.246	---	---	---	.392
Systematic tests																		
0.433	1.250	8	6	4130	423	26.5	42.0	38.5	133	0.243	0.046	334	0.242	0.108	184	0.985	47	0.087
.533	1.078			4720	477	29.5	54.3	41.0	125	.257	.040	447	.254	.134	307	2.59	75	.230
.733	.918			5010	507	31.4	62.5	43.7	125	.264	.038	606	.258	.186	466	6.09	121	.335
.533	1.258			3360	181	12.0	24.1	19.3	177	.173	.071	461	.170	.140	321	1.80	54.8	.060
	1.168			3620	200	12.7	27.4	19.5	174	.175	.069	548	.172	.217	403	3.10	70.2	.038
	1.078			3730	212	13.3	32.0	20.0	180	.151	.068	612	.176	.240	472	4.24	83.0	.150
	.887			4010	225	14.3	38.0	20.4	184	.159	.063	685	.182	.261	549	[illegible]	99.7	.217
	.819			4370	249	15.6	48.3	21.5	159	.131	.060	756	.167	.287	649	[illegible]	121	.313
	.730			4700	263	16.6	54.5	23.2	157	.201	.057	1086	.164	.400	949	17.5	174	.408
	.675			4960	283	17.5	61.1	24.7	153	.204	.041	1620	.173	.570	1480	41.0	256	.434
	.566			5090	290	22.1	64.5	25.5	140	.229	.047	2320	.141	.802	2660	103.5	378	.503
.933	1.256			3460	141	10.5	24.1	22.1	222	.137	.083	550	.149	.243	440	2.74	[illegible]	.052
	1.166			3620	145	10.4	27.3	21.1	202	.145	.068	462	.133	.250	525	4.17	73	.104
	1.076			3810	[illegible]	10.4	33.7	20.3	203	.152	.064	423	.140	.304	593	[illegible]	[illegible]	[illegible]
	[illegible]			3970	162	[illegible]	37.1	19.7	194	.157	.081	528	.149	.346	659	7.7	102	.215
	[illegible]			4240	173	11.0	43.1	[illegible]	[illegible]	.164	.076	560	.152	.397	820	11.5	125	[illegible]
	.782			4520	185	11.5	52.4	19.2	[illegible]	.172	.072	1327	.149	.440	1187	22.8	177	.411
	.675			4710	202	13.3	61.1	[illegible]	[illegible]	.153	.066	2430	.111	.812	2290	63.0	254	[illegible]
	.560			5220	213	22.1	65.3	25.0	140	.225	.037	2120	.141	.882	2680	109.1	374	.560
Restrictor position																		
0.483	0.775	1	6	3260	[illegible]	1.8	22.4	13.0	82	0.470	0.040	405	0.44	0.282	282	3.7	129	0.108
		2		3570	203	3.3	25.4	15.7	77	.374	.043	515	.35	.284	375	[illegible]	143	.151
		4		4070	236	7.3	35.3	20.0	106	.275	.049	695	.25	.311	558	5.7	151	.241
		6		4440	253	10.1	48.2	22.3	155	.137	.037	1017	.15	.363	877	16.1	174	.333
		8	1	3860	202	12.8	28.0	14.1	173	.177	.066	1210	.162	.472	1070	20.1	174	.162
			2	4020	228	14.3	35.0	17.1	163	.159	.060	1155	.173	.429	1015	19.2	[illegible]	.282
			4	4520	257	15.2	49.8	21.5	157	.196	.066	1100	.161	.393	960	14.2	178	.360
			6	4710	268	16.3	54.7	23.3	[illegible]	.201	.061	1085	.154	.382	942	15.0	178	.410
Combustor performance																		
0.935	---	8	---	2760	113	---	---	14.1	---	---	---	---	---	---	---	---	---	---
.935	---	16	---	3500	143	---	---	26.1	---	---	---	---	---	---	---	---	---	---
.780	---	8	---	3470	141	---	---	10.6	---	---	---	---	---	---	---	---	---	---
.780	---	16	---	3810	182	---	---	22.3	---	---	---	---	---	---	---	---	---	---
.643	---	8	---	2750	233	---	---	14.1	---	---	---	---	---	---	---	---	---	---
.643	---	16	---	3810	310	---	---	23.5	---	---	---	---	---	---	---	---	---	---

[a](Density)(Relative velocity)^2/2g.

[b](Density)(Relative velocity).

[c]Increase in heptane burned/heptane burned [illegible].

[d]Total flow, 0.6 lb/sec; all other tests, 0.9 lb/sec.



(a) Exploratory tests.

(b) Systematic tests.

Figure 1. - Combustor and restrictor configurations.

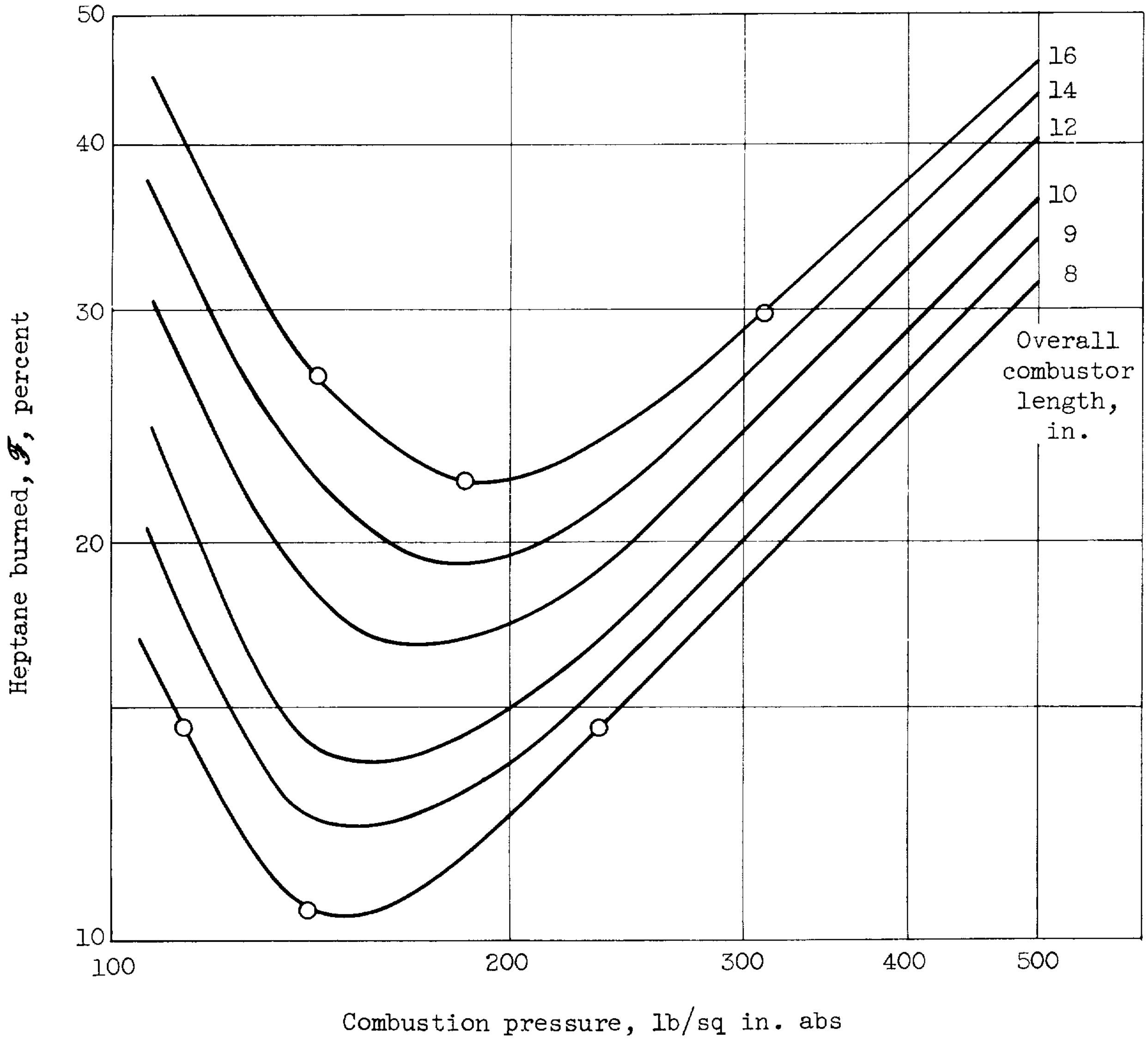
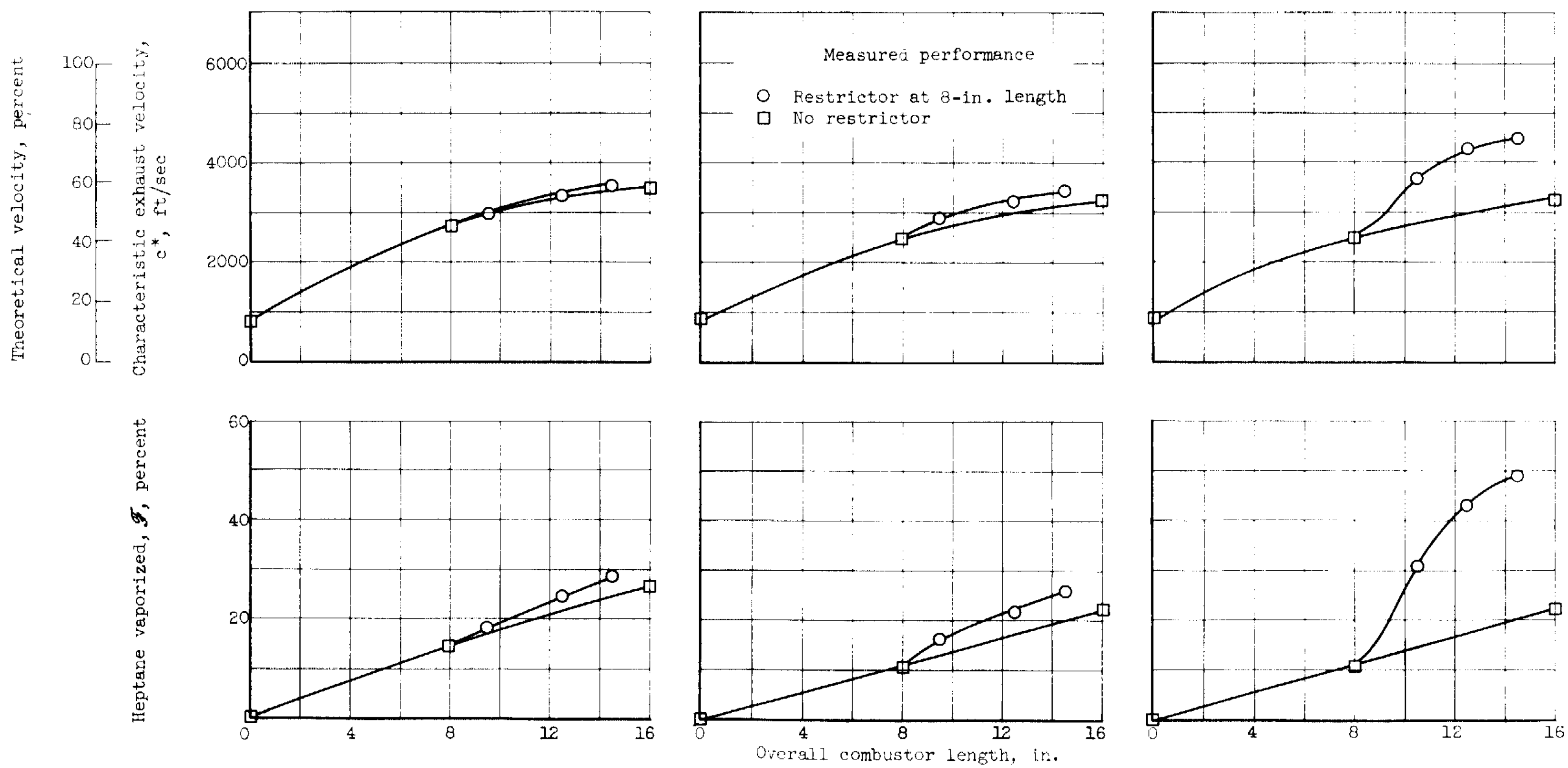


Figure 2. - Extrapolated performance map for combustor without area restrictor.

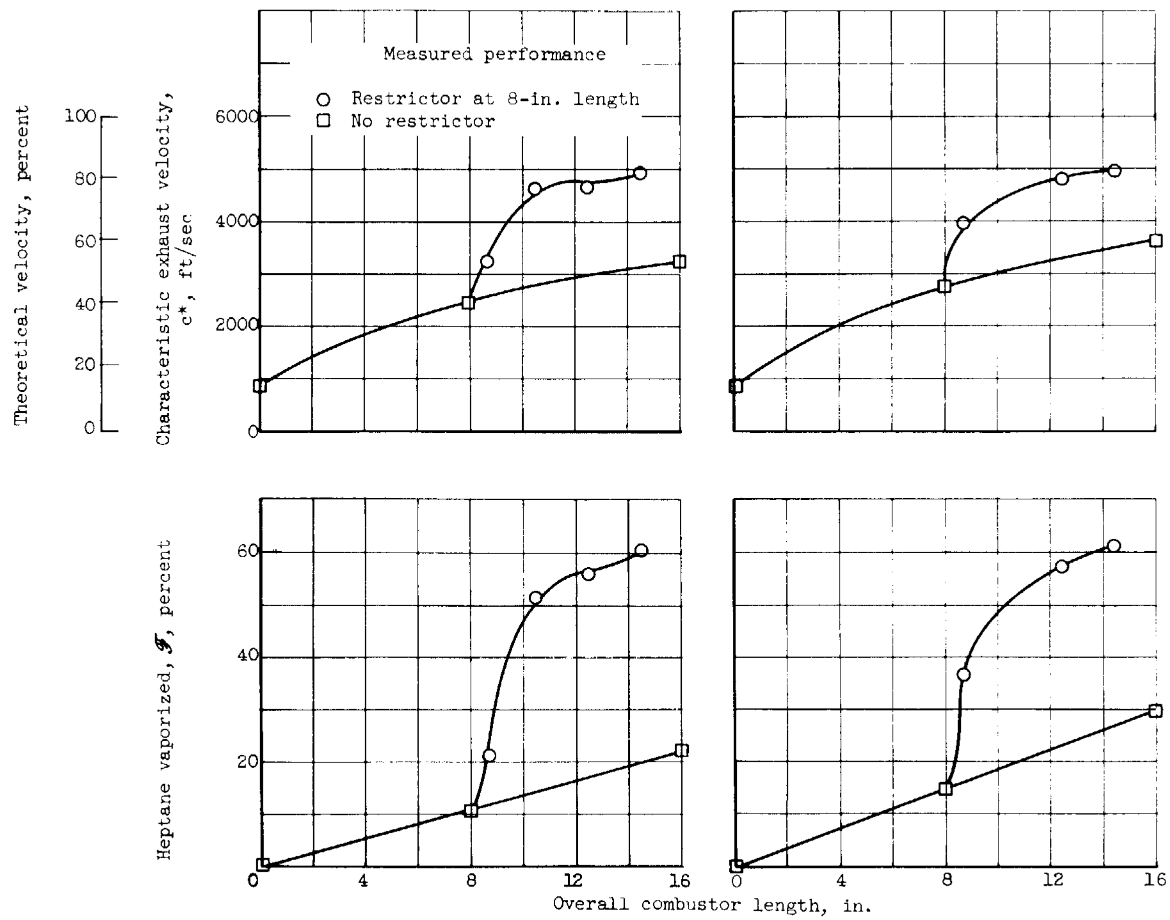


(a) Restrictor diameter, 1.37 inches; exhaust-nozzle diameter, 0.935 inch.

(b) Restrictor diameter, 1.37 inches; exhaust-nozzle diameter, 0.790 inch.

(c) Restrictor diameter, 0.893 inch; exhaust-nozzle diameter, 0.790 inch.

Figure 3. - Combustor performance with and without area restrictor.



(d) Restrictor diameter, 0.790 inch; exhaust-nozzle diameter, 0.790 inch.

(e) Restrictor diameter, 0.790 inch; exhaust-nozzle diameter, 0.593 inch.

Figure 3. - Concluded. Combustor performance with and without area restrictor.

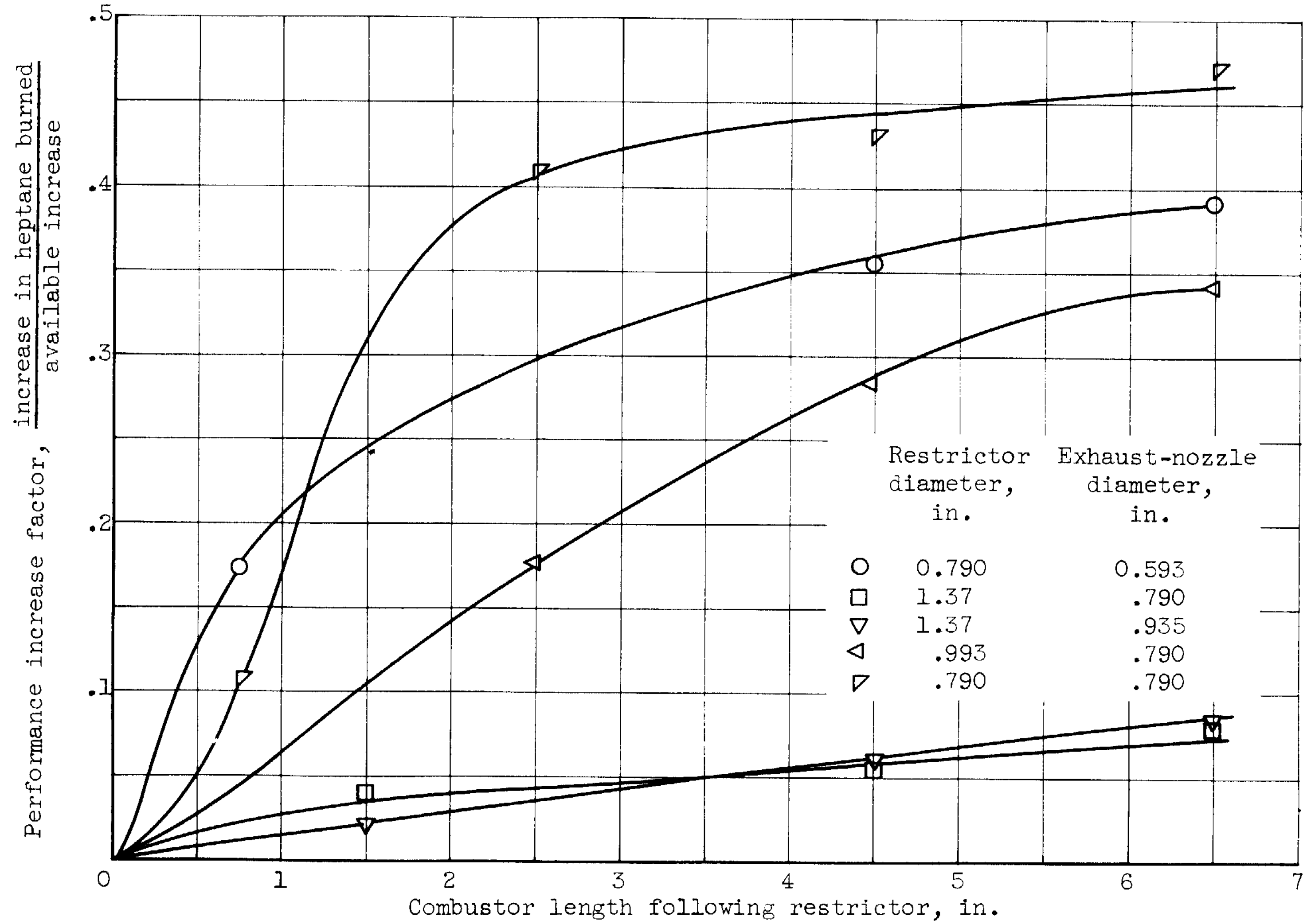


Figure 4. - Performance increase factor for exploratory test conditions.

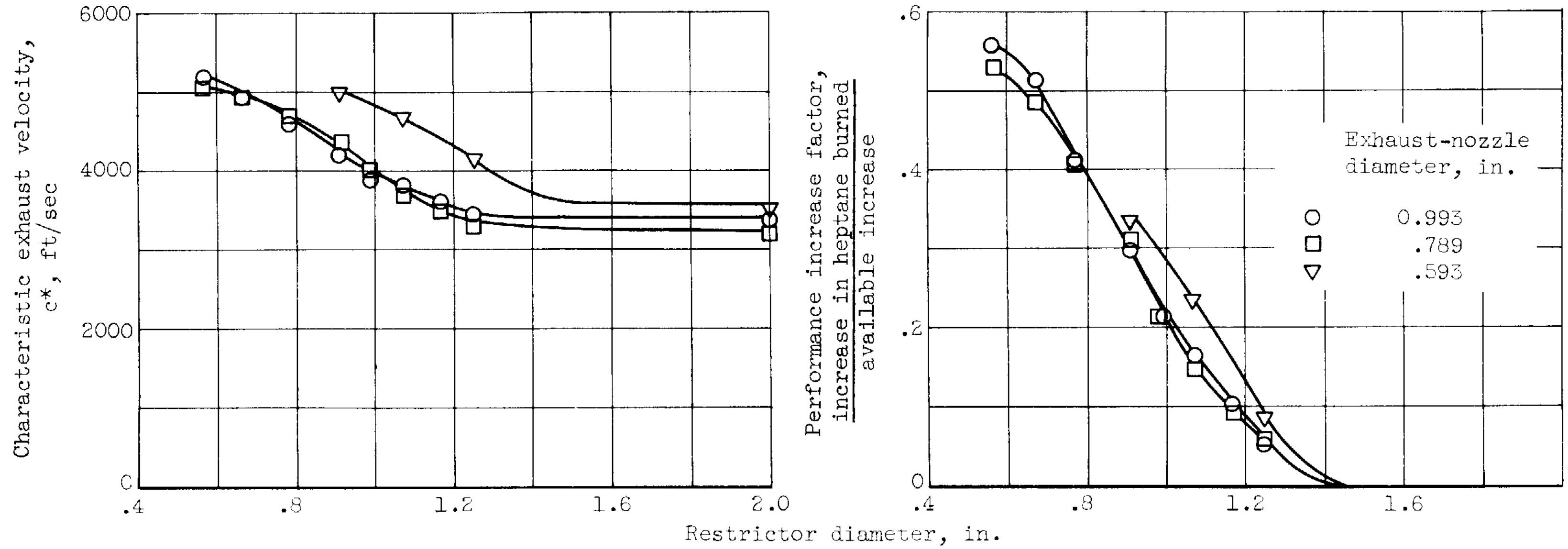


Figure 5. - Effect of restrictor diameter on combustor performance.

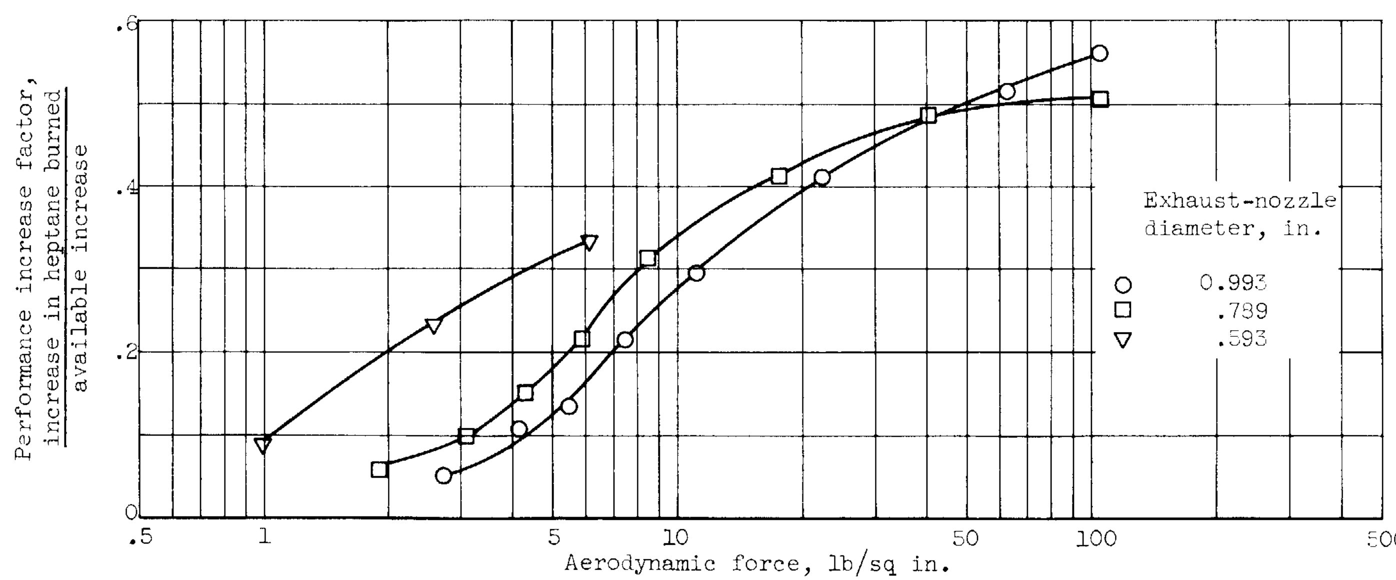


Figure 6. - Aerodynamic force and performance increase factor.

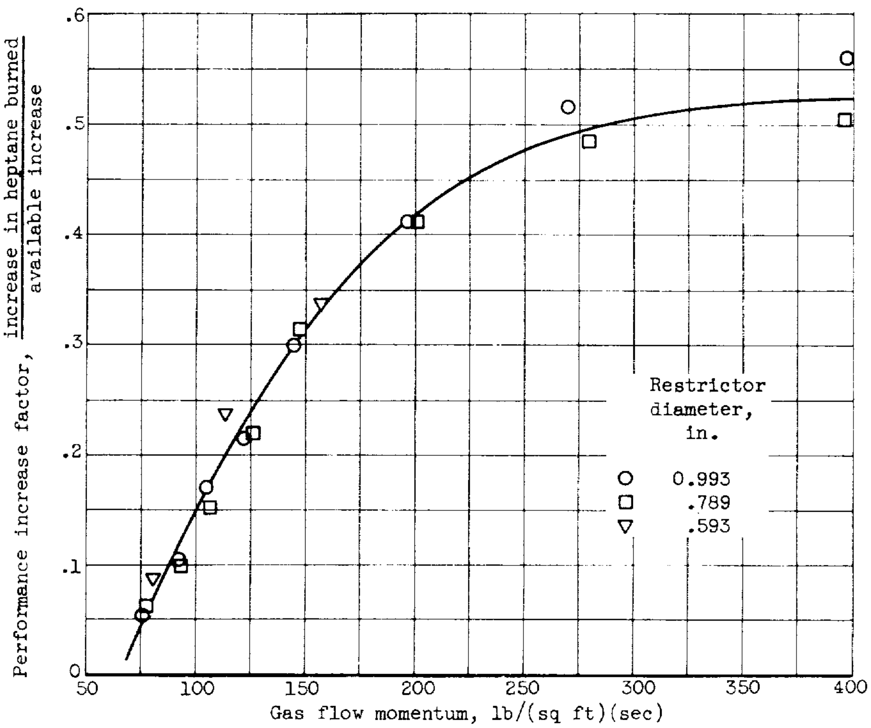


Figure 7. - Empirical correlation of performance increase factor and gas flow momentum.

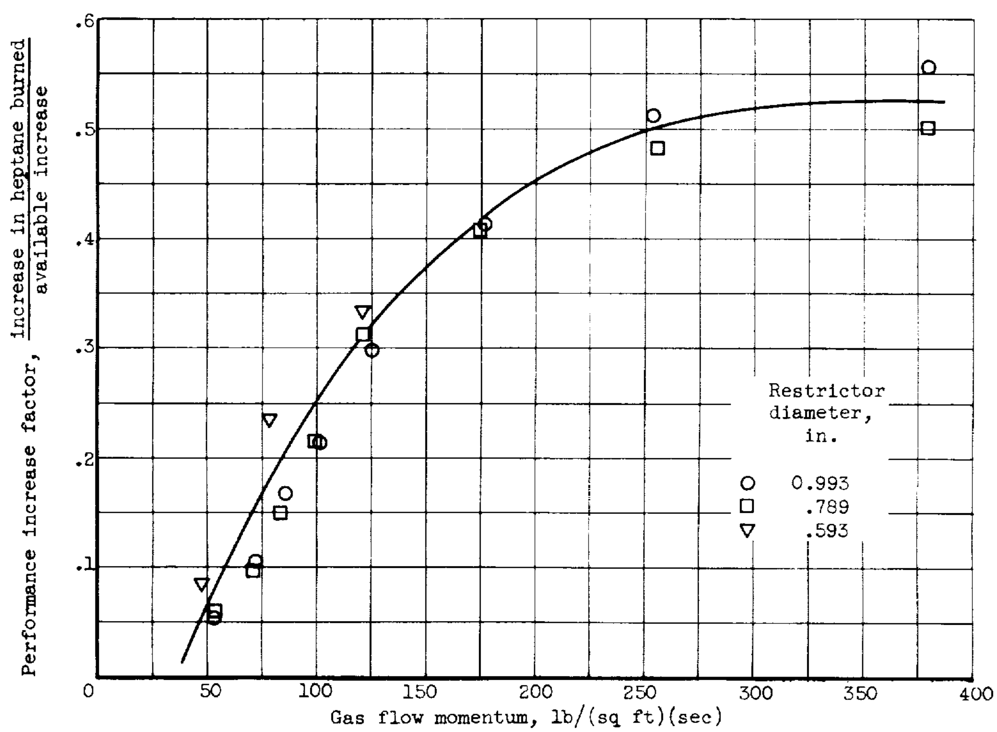


Figure 8. - Empirical correlation of performance increase factor and gas flow momentum relative to moving drops.

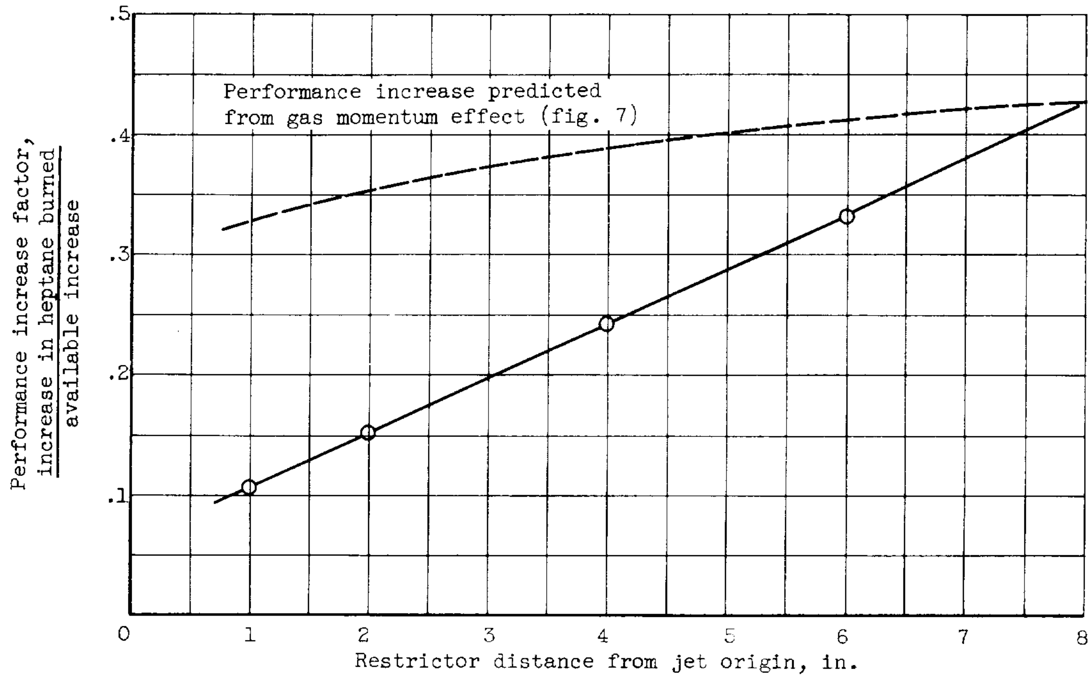


Figure 9. - Effect of restrictor position on performance increase factor.

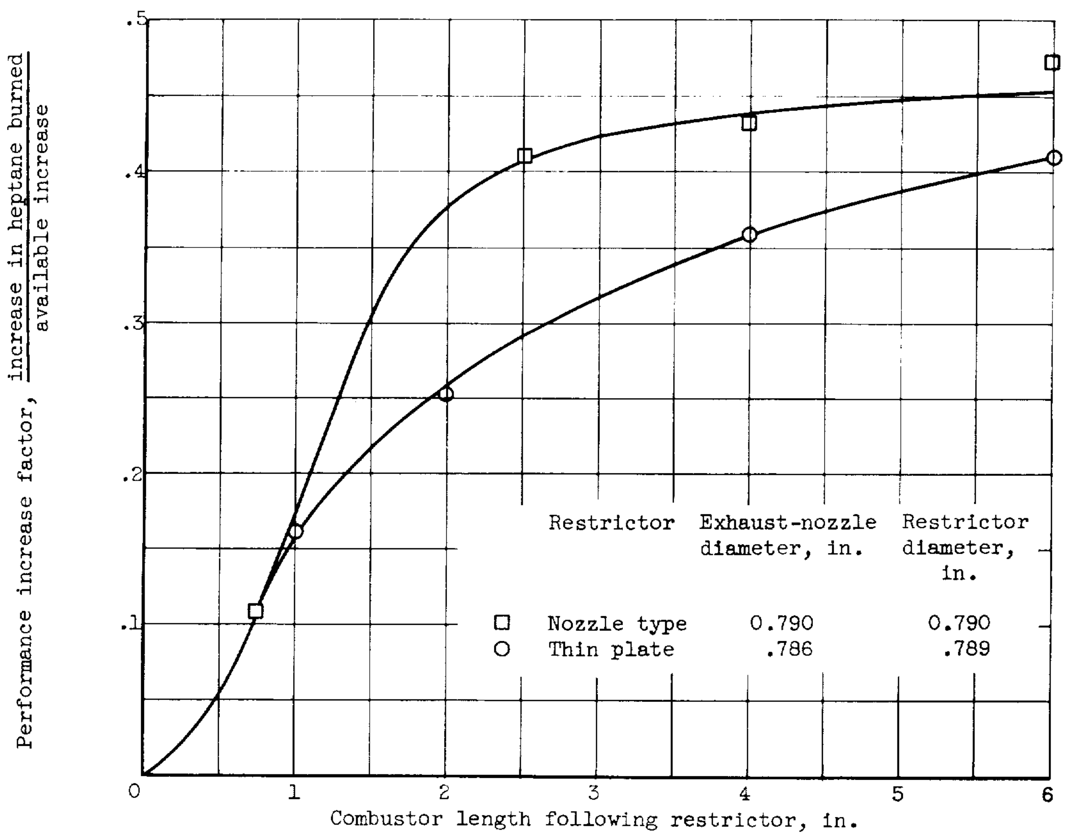


Figure 10. - Effect of restrictor contour on performance increase factor.